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## **Typhoon-ocean interaction: the ocean response to typhoons and its feedback to typhoon intensity - Synergy of observations and model simulations.**

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### **Background**

The lack of in situ measurement over the ocean has always been a major roadblock limiting our progress in understanding the interaction between TC and ocean more thoroughly and quantitatively.

With the success of THOREPX-PARC (T-PARC) (Wu et al. 2012a, b), the field program "Impact of Typhoons on the Ocean in the Pacific" (ITOP) (D'Asaro et al. 2013) was conducted in the summer of 2010. By closely coordinating with the DOTSTAR and TCS-10 programs, ITOP took special observations from dropwindsondes, floats, drifters deployed by airplanes and vessels, moorings and gliders, to measure the response of the upper ocean to typhoons. The experiment was conducted in simple, open ocean conditions and in the more complex conditions caused by ocean eddies, the Kuroshio and complex, shallow bathymetry. The measurements taken include surface waves, air-sea fluxes and the temperature, salinity and velocity structure of the upper ocean. These observations are used to understand key upper ocean processes, test upper ocean models, test key parameterizations of upper ocean physics used in these models and study feedback from the ocean to typhoon intensity.

### **Objectives**

It has been well demonstrated that the upper ocean thermal structure plays very important roles in affecting the typhoon-ocean interaction processes. In particular, the translation speed of the typhoon and the depth of the mixed layer are two most crucial factors in the cold wake response and its feedback to typhoon intensity. Meanwhile, the presence of warm or cold oceanic eddies can have subtle impact on the typhoon-ocean interaction. It has been shown that warm eddies support the rapid intensification of typhoons given the favorable atmospheric conditions.

With the abundant ITOP observation data on Typhoon Fanapi and Megi, this study is conducted to achieve the following goals: (1) Investigation of the roles of upper ocean thermal structures (eddies and wakes) in typhoon-ocean interaction; (2) Understanding the feedback of the typhoon-ocean interaction to typhoon intensity and structure evolution, and (3) Numerical simulation experiments (coupled model) with ITOP data.

### **Methods**

In order to create a reasonable initial typhoon structure, a new TC initialization method based on Ensemble Kalman Filter (EnKF) (Wu et al. 2010) is applied before conducting the high-resolution coupled model simulation. The ITOP period is selected to perform a single-domain ensemble reanalysis with 54-km horizontal resolution (hereafter

ITOP\_EnKF). The domain has 121\*91 grids and 35 vertical levels, covering the major TC-active area in the north Western Pacific. A 45-member initial ensemble is generated from NCEP FNL. The TC center position and minimum central sea level structure are assimilated every hour, and the azimuthal-mean 700-hPa tangential wind profiles observed by C-130 missions are assimilated when the reconnaissance flights are conducted.

In order to examine the impact of atmospheric forcing on the ocean prediction under Typhoon Megi, we collaborate with Dr. D.-S. Ko (NRL) and use an ocean nowcast/forecast system that covers the western Pacific Ocean and the eastern Asian marginal seas (EASNFS) to reconstruct the ocean field via atmospheric forcing from ITOP data. The model resolution is ~ 8 km in the study area and with 40 vertical levels with dense upper layers to further resolve upper-ocean variation. The altimetry data is assimilated within the ocean model to produce subsurface oceanic mesoscale features for the impact study. The atmospheric forcing is provided by an atmospheric model on a triple (54/18/6 km) nested grid that moves with the storm. The 10-m wind and sea level air pressure are applied to drive the ocean model.

Both Fanapi and Megi are simulated by a comprehensive full-physics coupled atmosphere-ocean model based on the WRF model and three-dimensional PWP ocean model, whereas the atmospheric and oceanic data are obtained during ITOP (18 August~ 25 October, 2010).

### **Results**

With the adequate observation data collected during the ITOP period, nine TCs are examined by using EnKF assimilation method to obtain reasonable TC analysis fields. Although in ITOP\_EnKF the TC advisory information (e.g., tracks and intensities) is not directly assimilated into the model, all typhoons can still form at the correct locations and their track analysis is fairly close to the observed track from JMA (Fig. 1).

Based on the above analysis (CTL), two model forecasts of Fanapi (not shown) are conducted with different initial conditions. In this case, TC intensity is closer to the observation, given that more assimilation data is available.

The high-resolution simulation of Megi from 0000 UTC 13 October to 0600 UTC 24 October is also initialized from the ensemble dataset by ITOP\_EnKF. It is shown that the track of the ensemble mean is relatively close to the best track of JMA (not shown). The minimum sea level pressure and maximum wind speed evolution from the ensemble mean are also investigated (Fig. 2). The results show that the intensity of the ensemble mean based on ITOP\_EnKF is consistent with observations, especially in terms of minimum

sea level pressure. It is found that assimilating the ITOP data with EnKF method can help conduct a new atmospheric analysis which matches the observation closely.

The above atmospheric analysis is further used to drive EASNFS to examine the ocean response in Megi (Fig. 3c). Compared with the SST cooling derived from satellites (Fig. 3a), it is shown that the ocean field driven from atmospheric forcing by ITOP\_EnKF is similar to observation results.

It has been indicated that the development of TC is sensitive to the upper ocean thermal structure. To further examine the interaction of TC and ocean, it is necessary to make use of a coupled atmosphere-ocean model (e.g., WRF and 3D-PWP ocean model). Significant characteristics of SST cooling in the South China Sea are presented in Figs. 3a-c, among which Fig. 3b in particular shows the SST cooling reaches  $-7^{\circ}\text{C}$  in Megi in the coupled model. In order to examine the impact of ocean on Megi, simulations from the coupled model are compared to that from the uncoupled model between 0000 UTC 15 October and 0000 UTC 24 October (Fig.4). Because the TC-induced SST cooling is not distinct before landfall on 03 UTC October 18, both simulations have similar results in intensity which are consistent with observation. However, the intensity for different runs at later times show large discrepancy due to the SST cooling of  $-7^{\circ}\text{C}$  after landfall in the coupled model simulation, whereas in the uncoupled model with fixed SST, the intensity in coupled model is closer to the reality.

## Summary

A synergy study is conducted with observations during ITOP and high-resolution coupled atmosphere-ocean model (WRF, 3D-PWP) simulations. To obtain a reasonable initial typhoon structure, a new TC initialization method based on EnKF is applied before model simulations. It is found that assimilating the ITOP data with EnKF method can help conduct a new atmospheric analysis which closely matches the observation. In addition, the ocean field can be driven from atmospheric forcing by ITOP\_EnKF. We can therefore analyze the above ocean field to investigate the roles of upper ocean thermal structure in typhoon-ocean interaction. By using the coupled atmosphere-ocean model in Megi, it is found that the intensity in the coupled model simulation is closer to actual observations than in the uncoupled model simulation due to the presence of SST cooling in the South China Sea, which is consistent with the SST change derived from satellite products.

## Ongoing works

Despite having created a dataset of atmosphere and ocean fields in Typhoons Fanapi, Megi, and Malakas (Archambault et al. 2013; Harr et al. 2013) using abundant ITOP observations, some issues remain to be clarified through the synergy study of observations and model simulations: For Fanapi, (1) What are the differences between using the one-dimension and three-dimension coupled models (collaborating with S. Chen and C. Lee)? (2) How did the TC-induced cold wake form, sustain and decay? (3) What is the oceanic feedback on the storm intensity? (4) What is the impact of ocean on Fanapi if the atmosphere analysis from ITOP\_EnKF is used to drive EASNFS (collaborating with D.-S. Ko and I-I Lin)? For Megi, (1) What leads to such a super-typhoon? (2) What is the role of the

cold wake? For Malakas, what are the effects of the ocean eddies and atmospheric vertical wind shear on TC evolution.

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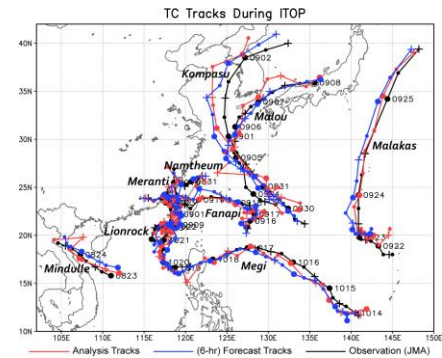


Figure 1: All TC tracks over the entire analysis period. Connection of the TC centers in each background 6-hr forecast (EnKF analysis) are shown in blue lines (red lines). Observed TC tracks from JMA are also plotted in black lines.

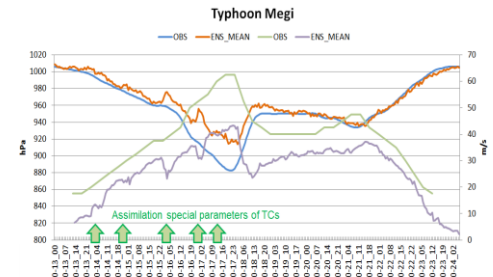


Figure 2: Sea level pressure evolution of Megi in observation (blue line), its ensemble mean (orange line), wind speed evolution in observation (green line), and its ensemble mean (purple line).

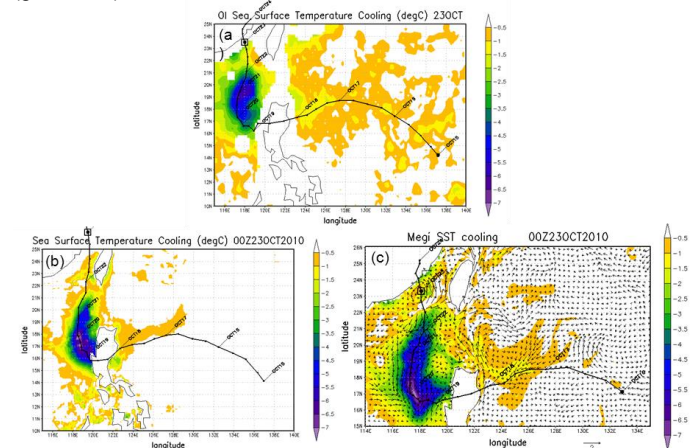


Figure 3: Sea Surface Temperature cooling derived (a) from EASNFS (Collaborating with D.-S. Ko of NRL), (b) from TMI-AMSRE satellite and (c) from coupled model simulations. The besttrack of Megi is shown with the black line.

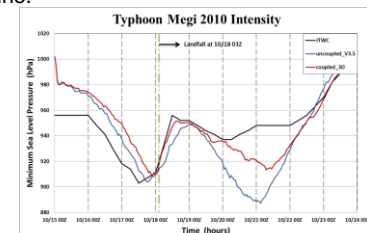


Figure 4: Minimum sea level pressure evolution of Megi with uncoupled (blue line) and coupled (red line) models. The landfall time is indicated with the green dotted line and the observed minimum sea level pressure from JTWC is shown with the black line.